Chapter 16
Dam Break Analysis

16-1. Introduction

a. *Corps policy*. It is the policy of the Corps of Engineers to design, construct, and operate dams safely (ER 1110-8-2(FR)). When a dam is breached, catastrophic flash flooding occurs as the impounded water escapes through the gap into the downstream channel. Usually, the response time available for warning is much shorter than that for precipitation-runoff floods, so the potential for loss of life and property damage is much greater.

b. *Hazard evaluation*. A hazard evaluation is the basis for selecting the performance standards to be used in dam design or in evaluating existing dams. When flooding could cause significant hazards to life or major property damage, the design flood selected should have virtually no chance of being exceeded. ER 1110-8-2(FR) provides dam safety standards with respect to the appropriate selection of an inflow design flood. If human life is at risk, the general requirement is to compute the flood using PMP. If lesser hazards are involved, a smaller flood may be selected for design. However, all dams should be designed to withstand a relatively large flood without failure even when there is apparently no downstream hazard involved under present conditions of development.

c. *Safety design*. Safety design includes studies to ascertain areas that would be flooded during the design flood and in the event of dam failure. The areas downstream from the project should be evaluated to determine the need for land acquisition, flood plain management, or other methods to prevent major damage. Information should be developed and documented suitable for releasing to downstream interests regarding the remaining risks of flooding.

d. *National Dam Safety Act*. The potential for catastrophic flooding due to dam failures in the 1960's and 1970's brought about passage of the National Dam Safety Act, Public Law 92-367. The Corps of Engineers became responsible for inspecting U.S. Federal and non-Federal dams, which met the size and storage limitations of the act, in order to evaluate their safety. The Corps inventoried dams; surveyed each State and Federal agency's capabilities, practices, and regulations regarding the design, construction, operation, and maintenance of the dams; developed guidelines for the inspection and evaluation of dam safety; and formulated recommendations for a comprehensive national program.

e. *Flood emergency documents*. In support of the National Dam Safety Program, flood emergency planning for dams was evaluated in the 1980's, and a series of documents were published: *Emergency Planning for Dams, Bibliography and Abstracts of Selected Publications* (HEC 1982a), *Flood Emergency Plan, Guidelines for Corps Dams*, Research Document 13 (HEC 1980), *Example Emergency Plan for Blue Marsh Dam and Lake* (HEC 1983a), and *Example Plan for Evacuation of Reading, Pennsylvania in the Event of Emergencies at Blue Marsh Dam and Lake* (HEC 1983b). The development of an emergency plan requires the identification of the type of emergencies to be considered, the gathering of needed data, performing the analyses and evaluations, and presenting the results. HEC Research Document 13 (HEC 1980) provides guidelines for each step of the process.

16-2. Dam Breach Analysis

a. *Causes of dam failures.* Dam failures can be caused by overtopping a dam due to insufficient spillway capacity during large inflows to the reservoir, by seepage or piping through the dam or along internal conduits, slope embankment slides, earthquake damage and liquification of earthen dams from earthquakes, or landslide-generated waves within the reservoir. Hydraulics, hydrodynamics, hydrology, sediment transport mechanics, and geotechnical aspects are all involved in breach formation and eventual dam failure. HEC Research Document 13 lists the prominent causes as follows:

(1) Earthquake.

(2) Landslide.

(3) Extreme storm.

(4) Piping.

(5) Equipment malfunction.

(6) Structural damage.

(7) Foundation failure.

(8) Sabotage.

b. *Dam breach characteristics.* The breach is the opening formed in the dam when it fails. Despite the fact that the main modes of failure have been identified as piping or overtopping, the actual failure mechanics are not well understood for either earthen or concrete dams. In previous attempts to predict downstream flooding due to dam failures, it was usually assumed that the dam failed completely and instantaneously. These assumptions of instantaneous and complete breaches were used for reasons of convenience when applying certain mathematical techniques for analyzing dam-break flood waves. The presumptions are somewhat appropriate for concrete arch-type dams, but they are not suitable for earthen dams and concrete gravity-type dams.

(1) Earthen dams, which exceedingly outnumber all other types of dams, do not tend to completely fail, nor do they fail instantaneously. Once a developing breach has been initiated, the discharging water will erode the breach until either the reservoir water is depleted or the breach resists further erosion. The fully formed breach in earthen dams tends to have an average width (b) in the range ($h_d < b < 3h_d$) where, h_d is the height of the dam. Breach widths for earthen dams are therefore usually much less than the total length of the dam as measured across the valley. Also, the breach requires a finite interval of time for its formation through erosion of the dam materials by the escaping water. The total time of failure may range from a few minutes to a few hours, depending on the height of the dam, the type of materials used in construction, and the magnitude and duration of the flow of escaping water. Piping failures occur when initial breach formation takes place at some point below the top of the dam due to erosion of an internal channel through the dam by escaping water. As the erosion proceeds, a larger and larger opening is formed. This is eventually hastened by caving-in of the top portion of the dam.

(2) Concrete gravity dams also tend to have a partial breach as one or more monolith sections formed during the dam construction are forced apart by the escaping water. The time for breach formation is in the range of a few minutes.

(3) Poorly constructed earthen dams and coal-waste slag piles which impound water tend to fail within a few minutes and have average breach widths in the upper range or even greater than those for the earthen dams mentioned above.

c. Dam breach parameters. The parameters of failure depend on the dam and the mode of failure. For flood hydrograph estimation, the breach is modeled assuming weir conditions, and the breach size, shape, and timing are the important parameters. The larger the breach opening and the shorter the time to total failure, the larger the peak outflow. HEC Research Document 13, Table 1, lists suggested breach parameters for earth-fill, concrete-gravity, and concrete-arch dams. There are two basic approaches used to determine possible breach sizes and times.

(1) The first approach uses statistically derived regression equations, like those formulated by MacDonald and Langridge-Monopolis (1984) and by Froelich (1987). Both sets of equations are based on actual data from dozens of historic dam failures. The MacDonald, and Langridge-Monopolis study was based on data from 42 constructed earth- and rock-fill dams. The Froelich study included data from constructed and landslide-formed earthen dams. Both studies resulted in a set of graphs and equations that can be used to predict the approximate size of the breach and the time it takes for the breach to reach its full size.

(2) The second approach is a physically based computer model called BREACH, developed by Dr. Danny Fread (1989) for the National Weather Service. The breach model uses sediment transport and hydraulic routing equations to simulate the formation of either a piping or overtopping type of failure. The model requires information about the physical dimensions of the dam, as well as a detailed description of the soil properties of the dam. Soils information includes D50 (mm), porosity, unit weight (lb/ft^3), internal friction angle, cohesive strength (lb/ft^2), and D90/D30. These parameters can be specified separately for the inner-core and outside-bank materials of a dam.

16-3. Dam Failure Hydrograph

a. Flow hydrograph. The flow hydrograph from a breached dam may be computed using traditional methods for flow routing through a reservoir and downstream channel. The reservoir routing approach is the same as routing for the spillway design flood, described in Chapter 14. Generally, a short time step is required because the breach formation and resulting reservoir outflow change rapidly with time.

b. Routing methods. The choice between hydraulic and hydrologic routing depends on many factors, including the nature of available data and accuracy required. The hydraulic method is the more accurate method of routing the unsteady flow from a dam failure flood through the downstream river. This technique simultaneously computes the discharge, water surface elevation, and velocity throughout the river reach. Chapter 9 of EM 1110-2-1417 describes the routing methods and applicability of routing techniques. Chapter 5 of EM 1110-2-1416 describes unsteady flow computations.

c. Geometry and surface area. The geometry and surface area of the reservoir can also affect the choice of method. For very narrow and long reservoirs where the dam is relatively large, the change of water level at the failed dam is rapid, and the unsteady flow method is useful. However, for very large reservoirs where the dam is small compared to the area of the lake, the change in water level is relatively slow and the storage routing method (Modified Puls) is economical in developing the failure hydrograph. Because of the rapid change in water level, small time periods are required for both methods.

d. *Height of downstream water*. The height of the water downstream of a dam (tailwater) also affects the outflow hydrograph in a failure analysis. It also affects the formation or nonformation of a bore in front of the wave.

e. *Deriving the peak outflow*. By assuming a rectangular cross section, zero bottom slope, and an instantaneous failure of a dam, the peak outflow can be derived by the mathematical expression originally developed by St. Venant, as follows:

$$Q_{\max} = \frac{8}{27} W_b \sqrt{g}\, Y_o^{3/2} \tag{16-1}$$

where

Y_o is the initial depth, W_b is the width of the breach, g is the gravity coefficient, and the water depth, y, just downstream of the dam is

$$y = \frac{4}{9} Y_o \tag{16-2}$$

This equation is applicable only for relatively long and narrow rectangular channels where the dam is completely removed. *Guidelines for Calculating and routing a Dam-Break Flood*, HEC Research Document No. 5 (HEC 1977) describes this approach.

f. *Failed dam outflow hydrograph*. The outflow hydrograph from a failed dam may also be approximated by a triangle. For instantaneous failure, a right triangle is applicable. The base represents the time to empty the reservoir volume, and the height represents the instantaneous peak outflow. In erosion analysis, the Office of Emergency Services, after consultation with other agencies, suggested an isosceles triangle. The rising side of the isosceles triangle is developed by assuming that half of the reservoir storage is required to erode the dam to natural ground level. The apex of the triangle represents the peak flow through the breach under the assumption that the flow occurs at critical depth.

g. *Potential for overtopping*. The Hydrologic Engineering Center's HEC-1 Flood Hydrograph Package (HEC 1990c) can be used to determine the potential for overtopping of dams by run off resulting from various proportions of the PMF. This technique is most appropriate for simulating breaches in earthen dams caused by overtopping. Other conditions may be approximated, however, such as instantaneous failure. This method makes six assumptions:

(1) Level-pool reservoir routing to determine time-history of pool elevation.

(2) Breach shape is a generalized trapezoid with bottom width and side slopes prespecified by the analyst.

(3) Bottom of the breach moves downward at a constant rate.

(4) Breach formation begins where the water surface in the reservoir reaches a prespecified elevation.

(5) Breach is fully developed when the bottom reaches a prespecified elevation.

(6) Discharge through the breach can be calculated independently of downstream hydraulics, i.e., critical depth occurs at or near the breach. A tailwater rating curve or a single cross section (assuming normal-depth for a rating) can be used to simulate submergence effects.

The total discharge from the dam at any instant is calculated by summing the individual flows through the low level outlet, over the spillway and top of the dam, and through the breach.

h. *Peak flow values*. With several calculations of theoretical flood peaks from assumed breaches, peak flow values may seem either too low or too high. One way of checking the reasonableness of the assumption is to compare the calculated values with historical failures. An envelope of estimated flood peaks from actual dam failures prepared by the Bureau of Reclamation is a good means of comparing such values. HEC Research Document No. 13, Figure 2, provides an envelope of experienced outflow rates from breached dams, as a function of hydraulic depth.

16-4. Dam Break Routing

a. *Dam-break flood hydrographs*. Dam-break flood hydrographs are dynamic, unsteady flow events.

Therefore, the preferred routing approach is to utilize a full unsteady flow routing model. The HEC-1 Flood Hydrograph package provides the capability to compute and route the inflow design flood and compute the breach and resulting hydrograph, but its channel routing is limited to hydrologic methods. The most appropriate HEC-1 approach is the Muskingum-Cunge option. The option uses a simple cross section plus reach slope and length to define a routing reach. No downstream backwater effects are considered. If simplified representations of the downstream river reaches are acceptable, an adequate routing may be obtained.

b. *St. Venant equations*. The St. Venant equations apply to gradually varied flow with a continuous profile. If features which control or interrupt the water surface profile exist along the main stem of the river or its tributaries, internal boundary conditions are required. These features include dams, bridges, roadway embankments, etc. If the structure is a dam, the total discharge is the sum of spillway flow, flow over the top of the dam, gated-spillway flow, flow through turbines, and flow through a breach, should a breach occur. The spillway flow and dam overtopping are treated as weir flow, with corrections for submergence. The gated outlet can represent a fixed gate or one in which the gate opening can vary with time. These flows can also be specified by rating curves which define discharge passing through the dam as a function of upstream water surface elevation.

c. *Unsteady flow computer programs*. There are an increasing number of available unsteady flow computer programs. The FLDWAV program is a generalized unsteady-flow simulation model for open channels. It replaces the DAMBRK, DWOPER, and NETWORK models, combining their capabilities and providing new hydraulic simulation procedures within a more user-friendly model structure (DeVries and Hromadka 1993). Given the long history of application by the National Weather Service, this program is likely the most capable for this purpose.

d. *FLDWAV*. FLDWAV can simulate the failure of dams caused by either overtopping or piping failure of the dam. The program can also represent the failure of two or more dams located sequentially on a river. The program is based on the complete equations for unsteady open-channel flow (St. Venant equations). Various types of external and internal boundary conditions are programmed into the model. At the upstream and downstream boundaries of the model (external boundaries), either discharges or water surface elevations, which vary with time, can be specified.

e. *Special features*. The following special features and capacities are included in FLDWAV: variable Δt and Δx computational intervals; irregular cross-sectional geometry; off-channel storage; roughness coefficients that vary with discharge or water surface elevation, and with distance along the waterway; capability to generate linearly interpolated cross sections and roughness coefficients between input cross sections; automatic computation of initial steady flow and water elevations at all cross sections along the waterway; external boundaries of discharge or water surface elevation time series (hydrographs), a single-valued or looped depth-discharge relation (tabular or computed); time-dependent lateral inflows (or outflows); internal boundaries enable treatment of time-dependent dam failures, spillway flows, gate controls, or bridge flows, or bridge-embankment overtopping flow; short-circuiting of floodplain flow in a valley with a meandering river; levee failure and/or overtopping; a special computational technique to provide numerical stability when treating flows that change from supercritical to subcritical , or conversely, with time and distance along the waterway; and an automatic calibration technique for determining the variable roughness coefficient by using observed hydrographs along the waterway.

f. *UNET*. The unsteady flow program UNET (HEC 1995) has a dam-break routing capability. However, there has been limited application of this feature. UNET could be used to route the outflow hydrograph computed in an HEC-1 runoff-dam break model. Both programs can read and write hydrographs using the HEC Data Storage System, HEC-DSS (HEC 1995a).

16-5. Inundation Mapping

a. *Preparation of maps*. To evaluate the effects of dam failure, maps should be prepared delineating the area which would be inundated in the event of failure. Land uses and significant development or improvements within the area of inundation should be indicated. The maps should be equivalent to or more detailed than the USGS quadrangle maps, 7.5-min series, or of sufficient scale and detail to identify clearly the area that should be evacuated if there is evident danger of failure of the dam. Copies of the maps should be distributed to local government officials for use in the development of an evacuation plan. The intent of the maps is to develop evacuation procedures in case of collapse of the dam, so the travel time of the flood wave should be indicated on every significant habitation area along the river channel.

b. *Evaluation of hazard potential*. To assist in the evaluation of hazard potential, areas delineated on inundation maps should be classified in accordance with the degree of occupancy and hazard potential. The potential for loss of life is affected by many factors, including but not limited to the capacity and number of exit roads to higher ground and available transportation. Hazard potential is greatest in urban areas. The evaluation of hazard potential should be conservative because the extent of inundation is usually difficult to delineate precisely.

c. *Hazard potential for recreation areas*. The hazard potential for affected recreation areas varies greatly, depending on the type of recreation offered, intensity of use, communications facilities, and available transportation. The potential for loss of life may be increased where recreationists are widely scattered over the area of potential inundation because they would be difficult to locate on short notice.

d. *Industries and utilities*. Many industries and utilities requiring substantial quantities of water are located on or near rivers or streams. Flooding of these areas and industries, in addition to causing the potential for loss of life, can damage machinery, manufactured products, raw materials and materials in process of manufacture, plus interrupt essential community services.

e. *Least hazard potential*. Rural areas usually have the least hazard potential. However, the potential for loss of life exists, and damage to large areas of intensely cultivated agricultural land can cause high economic loss.

f. *Evacuation plans*.

(1) Evacuation plans should be prepared and implemented by the local jurisdiction controlling inundation areas. The assistance of local civil defense personnel, if available, should be requested in preparation of the evacuation plan. State and local law enforcement agencies usually will be responsible for the execution of much of the plan and should be represented in the planning effort. State and local laws and ordinances may require that other state, county, and local government agencies have a role in the preparation, review, approval, or execution of the plan. Before finalization, a copy of the plan should be furnished to the dam agency or owner for information and comment.

(2) Evacuation plans will vary in complexity in accordance with the type and degree of occupancy in the potentially affected area. The plans may include delineation of the area to be evacuated; routes to be used; traffic control measures; shelter; methods of providing emergency transportation; special procedures for the evacuation and care of people from institutions such as hospitals, nursing homes, and prisons; procedures for securing the perimeter and for interior security of the area; procedures for the lifting of the evacuation order and reentry to the area; and details indicating which organizations are responsible for specific functions and for furnishing the materials, equipment, and personnel resources required. HEC Research Documents 19 and 20 provide example emergency plans and evacuation plans, respectively (HEC 1983a and b).